

# Optimization of a neutrino factory for non-standard interactions

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in collaboration with M. Lindner, T. Ota, J. Sato, and W. Winter



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# Outline

1

## Non-standard interactions in oscillation experiments

- The general formalism
- NSI in a neutrino factory
- Analytical treatment of NSI in a neutrino factory

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## Optimization of a neutrino factory in the presence of NSI

- Simulation details
- Optimization of muon energy
- Optimization of baselines

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## Summary and conclusions

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- Lagrangian:

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- We will focus on **NSI in the propagation (NC NSI)** in the following.

# NSI in oscillation experiments

- Compared to charged lepton flavour violation experiments: Interference between standard and non-standard amplitudes is possible  
⇒ NSI effects suppressed only by  $|\varepsilon|$  instead of  $|\varepsilon|^2$ .

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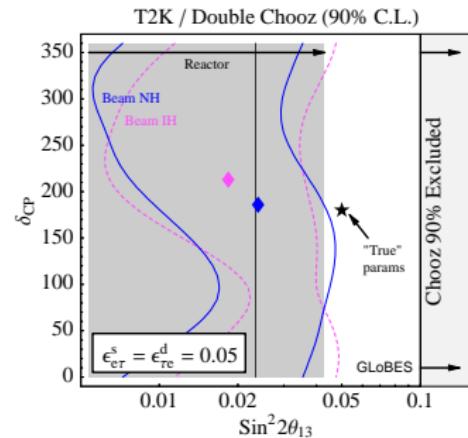
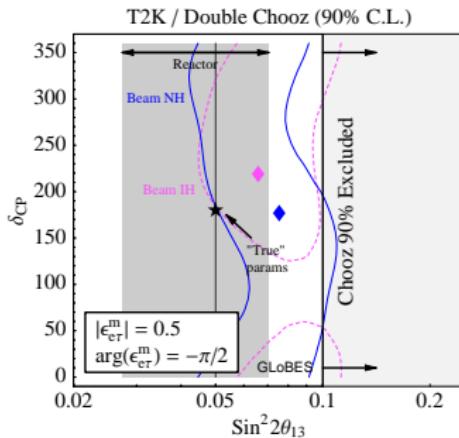
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JK Ota Lindner Phys. Rev. D77 (2008) 013007

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  - Mismatch** between standard oscillation fits to different experiments
  - Different optimization strategy**

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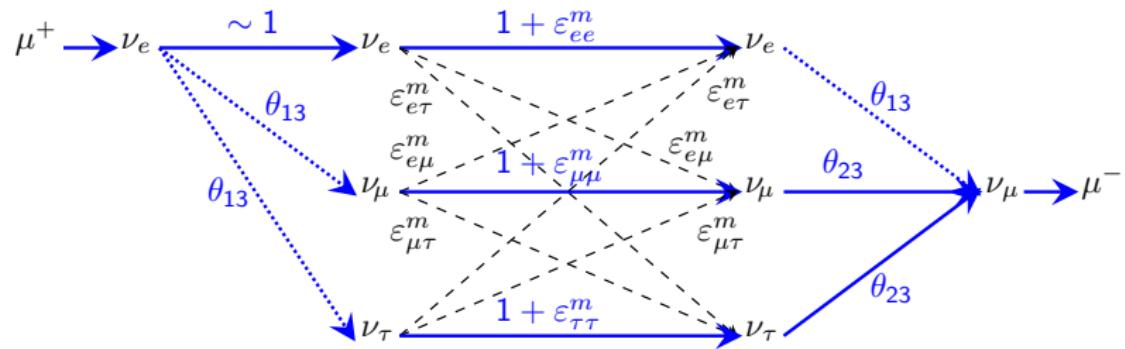
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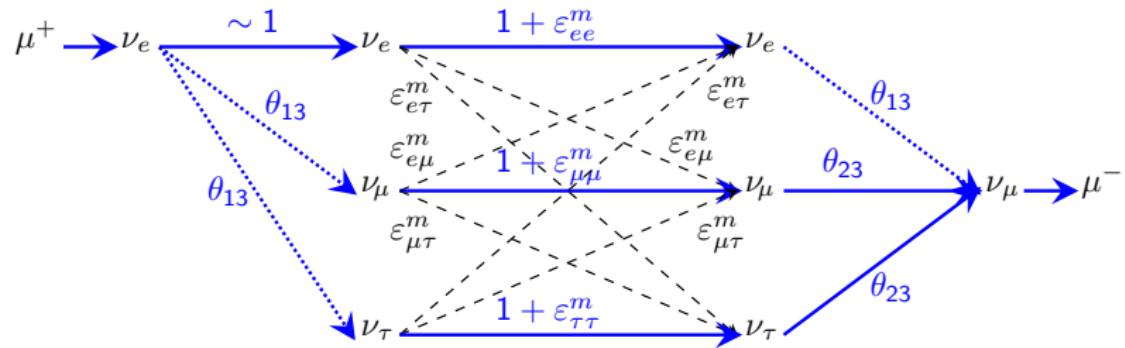
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## Summary and conclusions

# NSI in the NF appearance channel

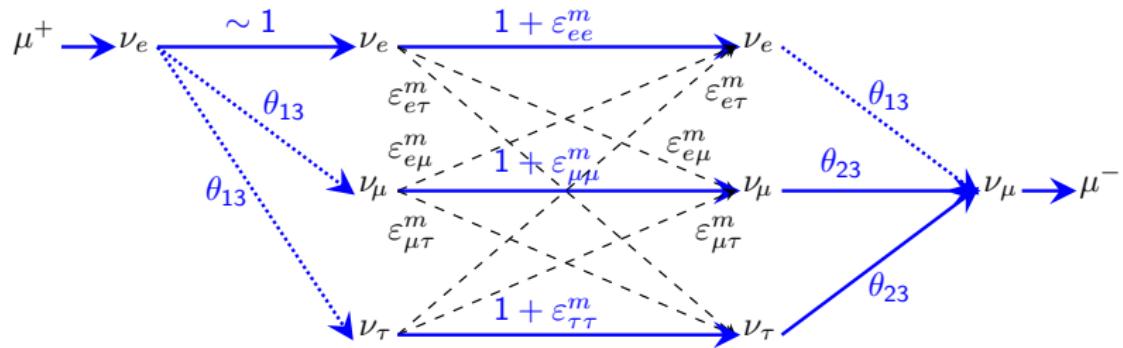


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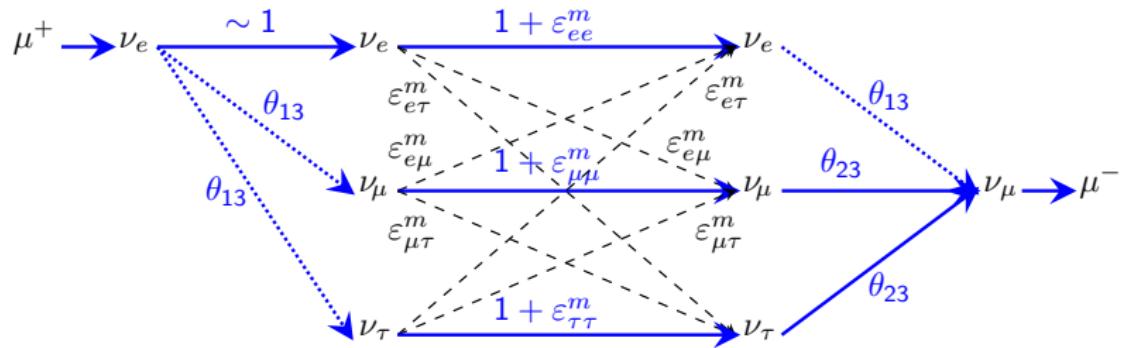
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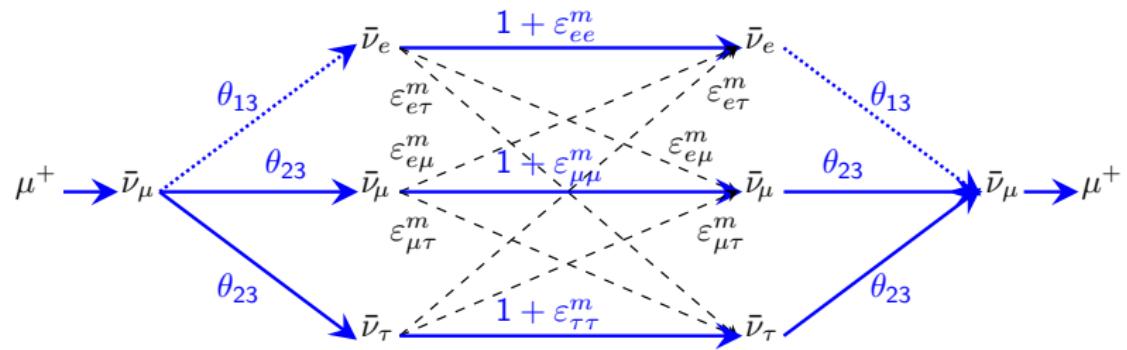


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- Assume  $\varepsilon \sim \theta_{13}$
- NSI paths with same level of suppression as standard path:

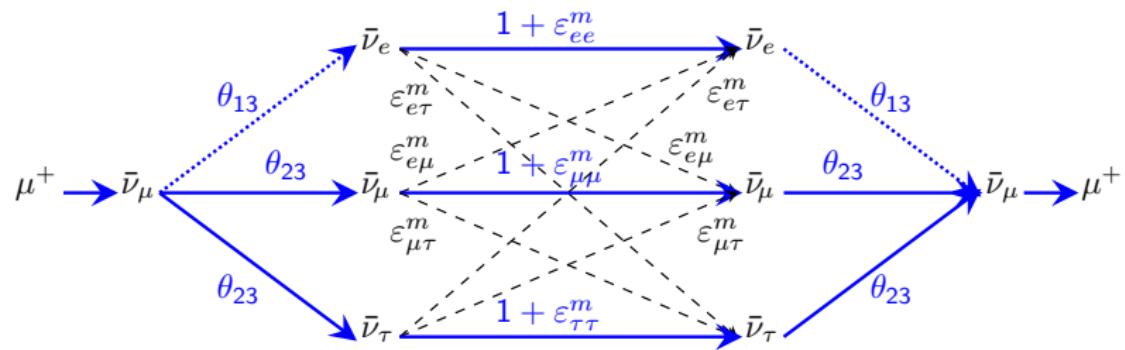
$$\mu^+ \rightarrow \nu_e \xrightarrow{\varepsilon_{e\mu}^m} \nu_\mu \rightarrow \mu^-$$

$$\mu^+ \rightarrow \nu_e \xrightarrow{\varepsilon_{e\tau}^m} \nu_\tau \xrightarrow{\theta_{23}} \nu_\mu \rightarrow \mu^-$$

# NSI in the NF disappearance channel

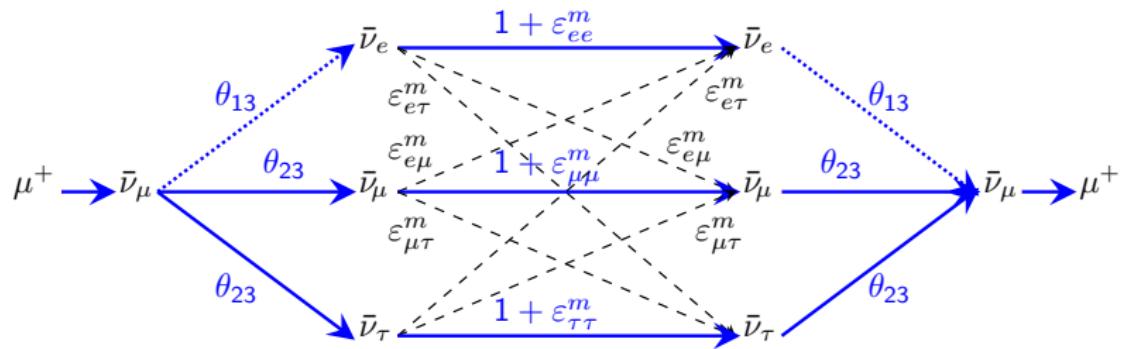


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- Standard path (unsuppressed):  $\mu^+ \rightarrow \bar{\nu}_\mu \rightarrow \bar{\nu}_\mu \rightarrow \mu^+$
- Dominant NSI paths:

$$\begin{aligned} \mu^+ &\rightarrow \bar{\nu}_\mu \xrightarrow{\epsilon_{\mu\mu}^m} \bar{\nu}_\mu \rightarrow \mu^+ \\ \mu^+ &\rightarrow \bar{\nu}_\mu \xrightarrow{\theta_{23}} \bar{\nu}_\tau \xrightarrow{\epsilon_{\tau\tau}^m} \bar{\nu}_\tau \xrightarrow{\theta_{23}} \bar{\nu}_\mu \rightarrow \mu^+ \\ \mu^+ &\rightarrow \bar{\nu}_\mu \xrightarrow{\epsilon_{\mu\tau}^m} \bar{\nu}_\tau \xrightarrow{\theta_{23}} \bar{\nu}_\mu \rightarrow \mu^+ \end{aligned}$$

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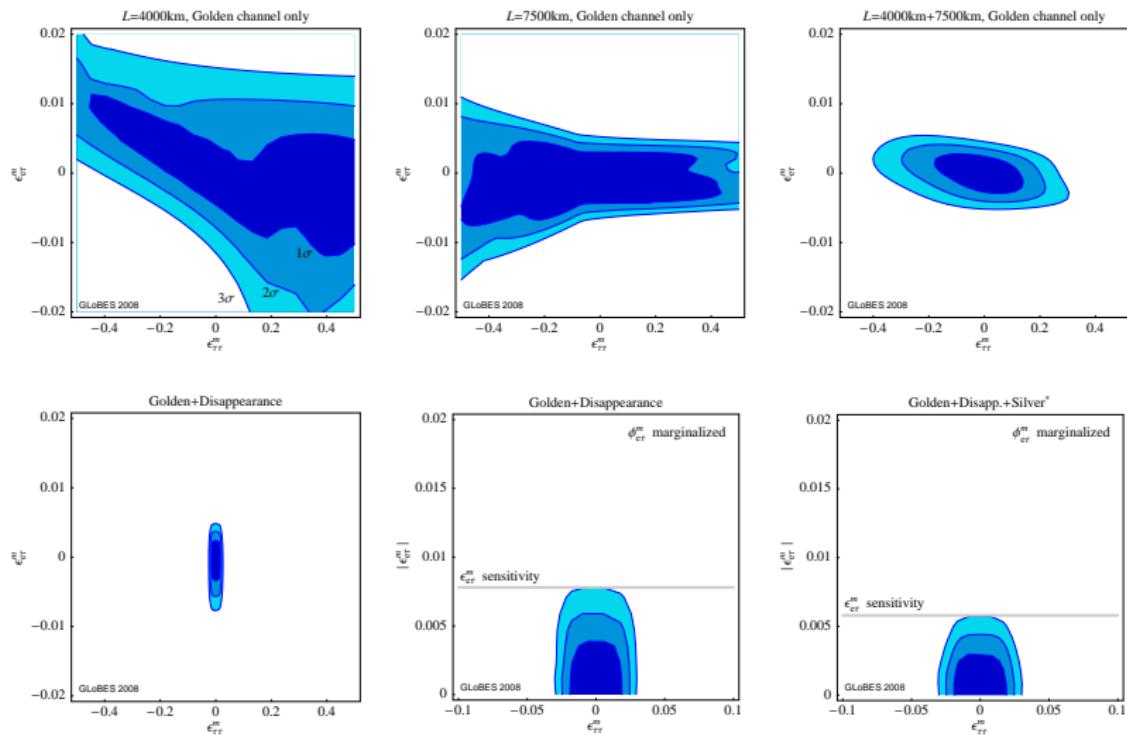
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- Already at this level, one can see that **the Silver channel is not needed** to detect NSI.

# Relevant oscillation channels for $\varepsilon_{e\tau}^m$ and $\varepsilon_{\tau\tau}^m$ sensitivity



Ribeiro Minakata Nunokawa Uchinami Zukanovich-Funchal JHEP **0712** (2007) 002, JK Ota Winter arXiv:0804.2261

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- $\epsilon_{e\tau}^m$
  - $\epsilon_{\mu\tau}^m$
  - $\epsilon_{\tau\tau}^m$
- } Most interesting

# Classification of NSI in a neutrino factory — Summary

- For the NF optimization, we need to consider only  $\epsilon_{e\tau}^m$ ,  $\epsilon_{\mu\tau}^m$ , and  $\epsilon_{\tau\tau}^m$ .
- We expect:
  - The Golden channel will be sensitive to  $\epsilon_{e\tau}^m$ .
  - The Silver channel will be sensitive to  $\epsilon_{e\tau}^m$ , but will not be needed.
  - The disappearance channel will be sensitive to  $\epsilon_{\mu\tau}^m$  and  $\epsilon_{\tau\tau}^m$ .

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## Oscillations with neutral current NSI

$$P_{\nu_\alpha^s \rightarrow \nu_\beta^d} = |\langle \nu_\beta | e^{-i(H + V_{\text{NSI}})L} | \nu_\alpha \rangle|^2$$

$$V_{\text{NSI}} = \sqrt{2} G_F N_e \begin{pmatrix} \varepsilon_{ee}^m & \varepsilon_{e\mu}^m & \varepsilon_{e\tau}^m \\ \varepsilon_{e\mu}^{m*} & \varepsilon_{\mu\mu}^m & \varepsilon_{\mu\tau}^m \\ \varepsilon_{e\tau}^{m*} & \varepsilon_{\mu\tau}^{m*} & \varepsilon_{\tau\tau}^m \end{pmatrix}$$

# Analytic expression for $P_{e\mu}$ including $|\varepsilon_{e\tau}^m|$

$$\begin{aligned}
 P_{e\mu}^{\text{NSI}} \simeq & P_{e\mu}^{\text{SO}} - 2 |\varepsilon_{e\tau}^m| \sin 2\theta_{13} \sin 2\theta_{23} s_{23} \sin(\delta_{\text{CP}} + \phi_{e\tau}^m) \mathcal{F}^{\text{MB}} \mathcal{F}^{\text{Res}} \sin \Delta \\
 & - 2 |\varepsilon_{e\tau}^m| \sin 2\theta_{13} \sin 2\theta_{23} s_{23} \cos(\delta_{\text{CP}} + \phi_{e\tau}^m) \mathcal{F}^{\text{MB}} \mathcal{F}^{\text{Res}} \cos \Delta \\
 & + 4 |\varepsilon_{e\tau}^m| \sin 2\theta_{13} c_{23} s_{23}^2 \cos(\delta_{\text{CP}} + \phi_{e\tau}^m) \hat{A} (\mathcal{F}^{\text{Res}})^2 \\
 & - 2 |\varepsilon_{e\tau}^m| \alpha \sin 2\theta_{12} \sin 2\theta_{23} c_{23} \sin \phi_{e\tau}^m \mathcal{F}^{\text{MB}} \mathcal{F}^{\text{Res}} \sin \Delta \\
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 & - 4 |\varepsilon_{e\tau}^m| \alpha \sin 2\theta_{12} s_{23} c_{23}^2 \cos \phi_{e\tau}^m \frac{1}{\hat{A}} (\mathcal{F}^{\text{MB}})^2 \\
 & + 4 |\varepsilon_{e\tau}^m|^2 c_{23}^2 s_{23}^2 \hat{A}^2 (\mathcal{F}^{\text{Res}})^2 \\
 & - 2 |\varepsilon_{e\tau}^m|^2 \sin^2 2\theta_{23} \hat{A} \mathcal{F}^{\text{MB}} \mathcal{F}^{\text{Res}} \cos \Delta \\
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 \end{aligned}$$

$$\hat{A} \equiv \pm a_{CC}/\Delta m_{31}^2 = \pm 2\sqrt{2}EG_F N_e / \Delta m_{31}^2,$$

Matter potential

$$\Delta \equiv \Delta m_{31}^2 L / 4E ,$$

Vacuum oscillation phase

$$\mathcal{F}^{\text{Res}} \equiv \sin[(1 - \hat{A})\Delta]/(1 - \hat{A}) ,$$

Maximal at matter resonance

$$\mathcal{F}^{\text{MB}} \equiv \sin(\hat{A}\Delta) = \sin \left( \pm \frac{G_F}{\sqrt{2}} N_e L \right) .$$

Vanishes at magic baseline

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- Strong correlations, even at magic baseline

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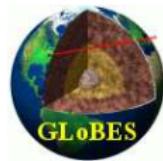
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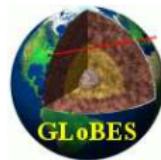
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Huber Lindner Winter Comput. Phys. Commun. **167** (2005) 195,  
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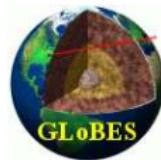
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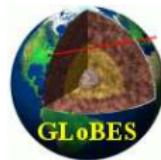
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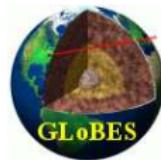
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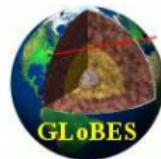
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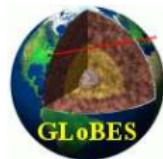
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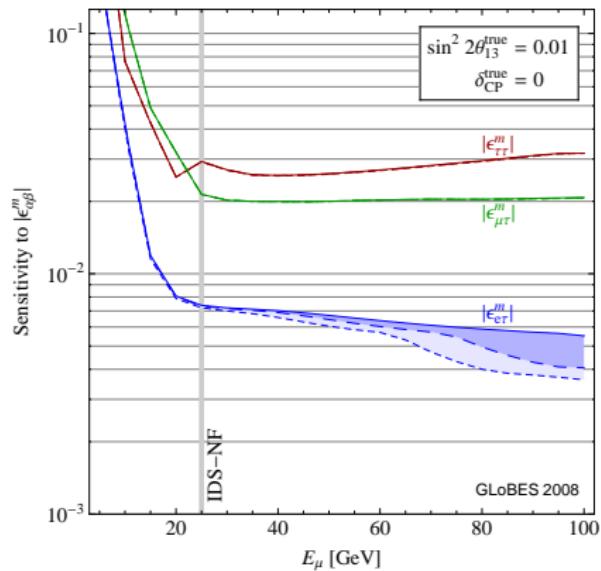
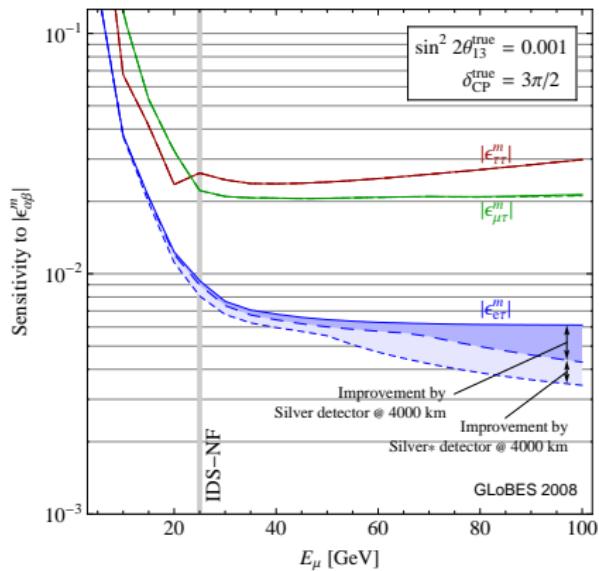
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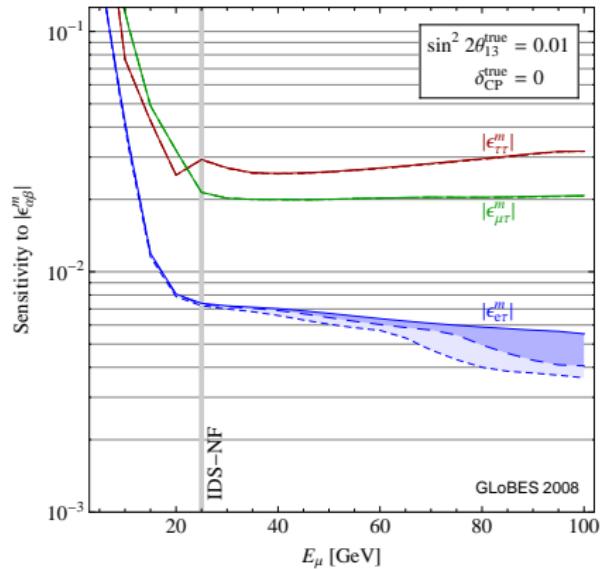
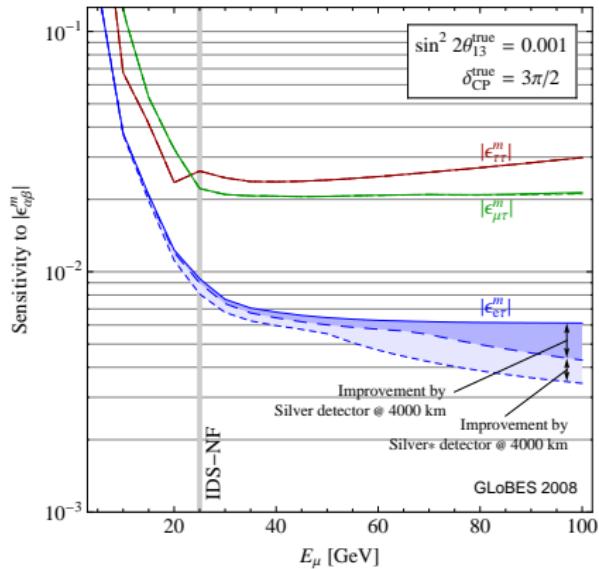
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JK Ota Winter arXiv:0804.2261

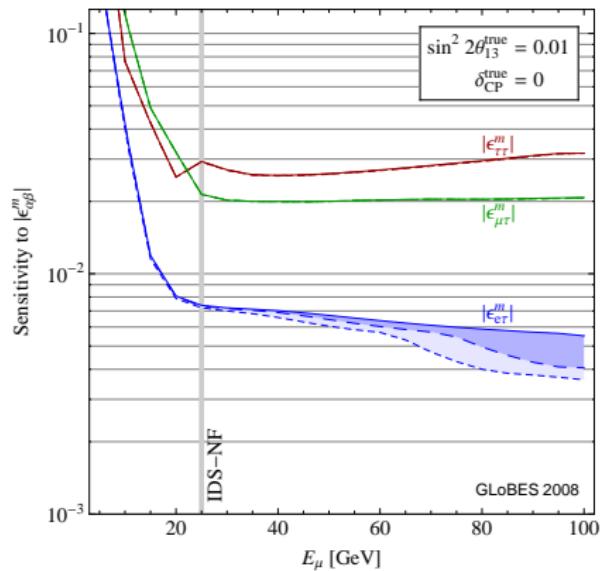
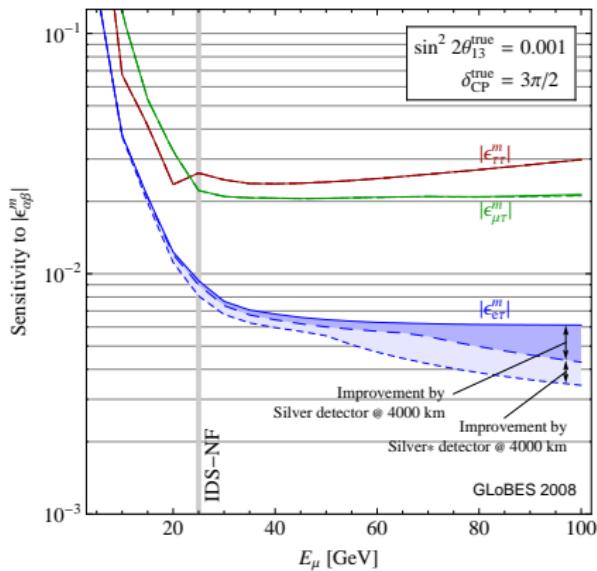
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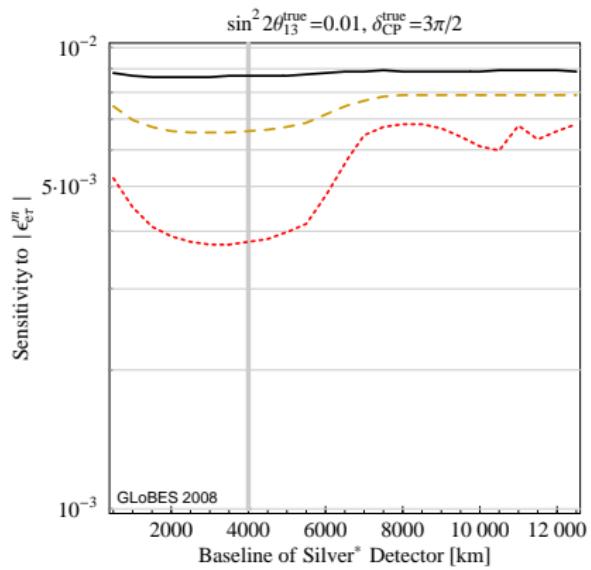
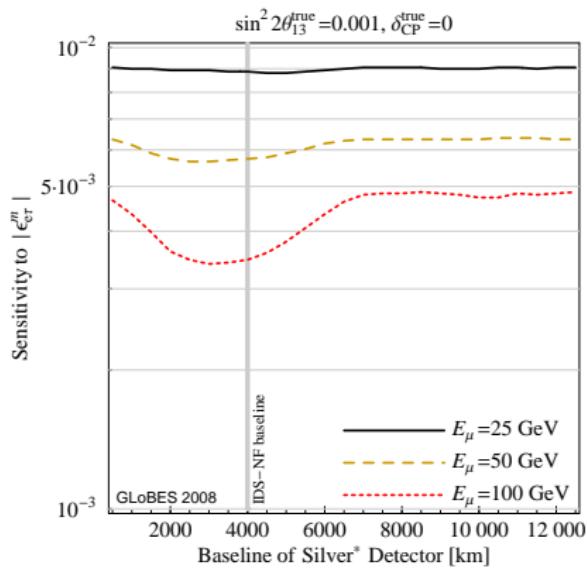
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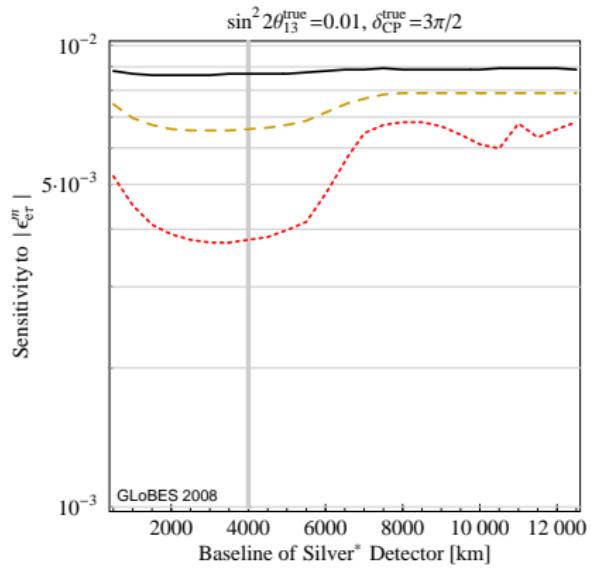
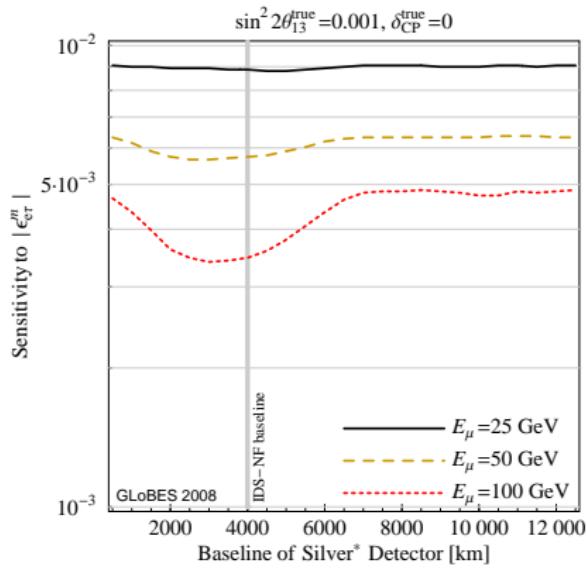
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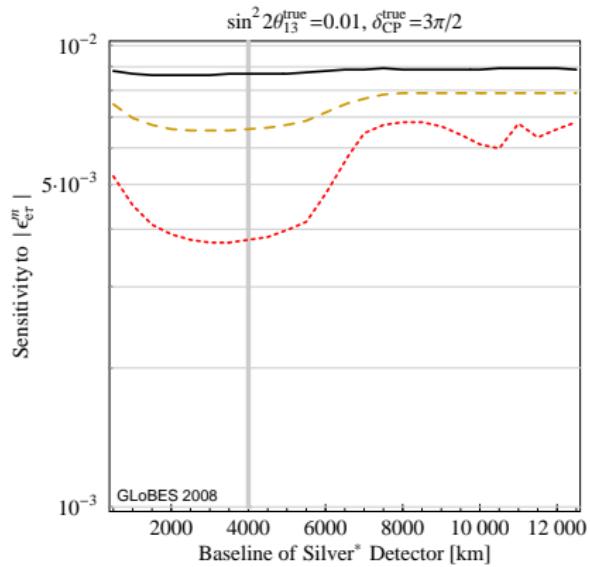
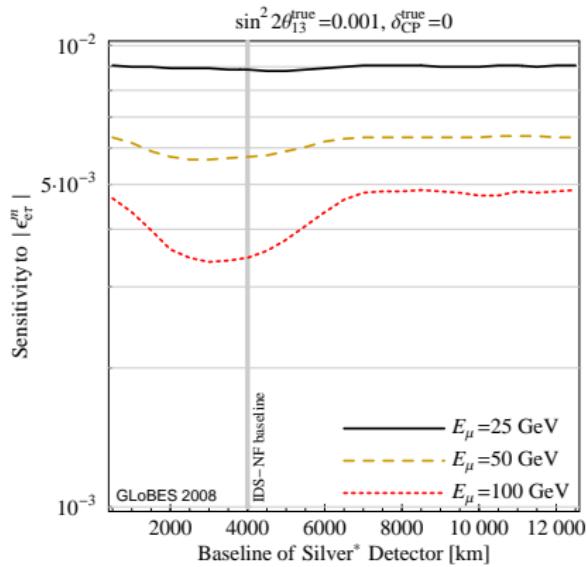


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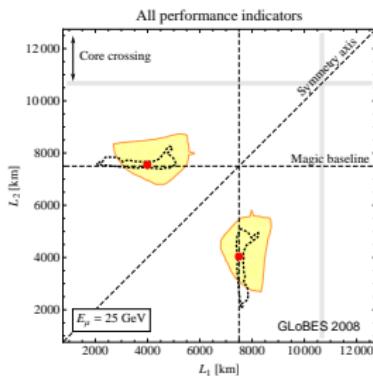
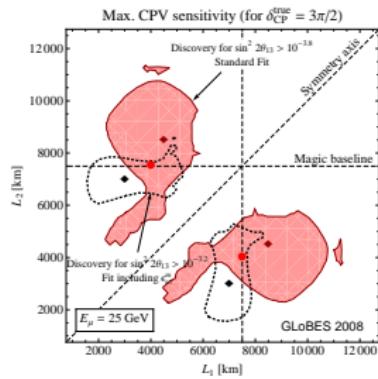
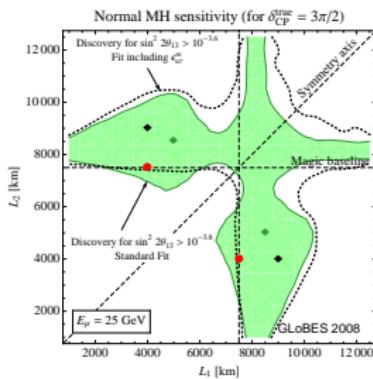
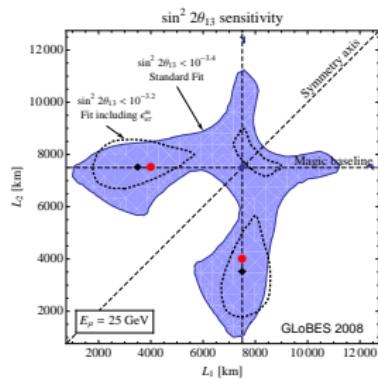
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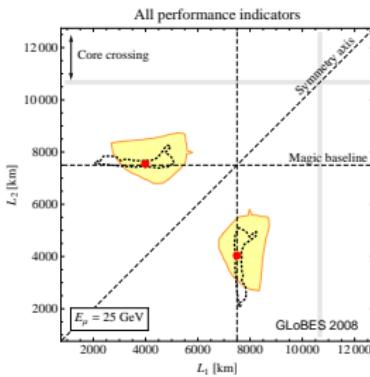
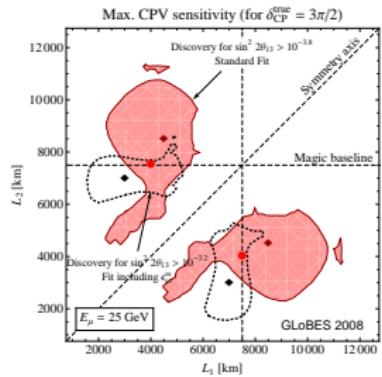
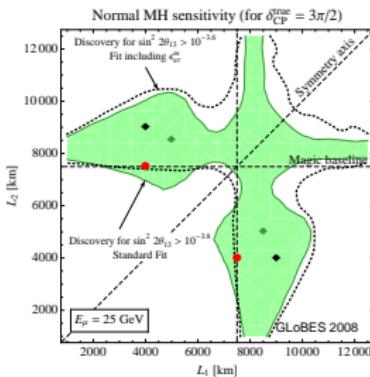
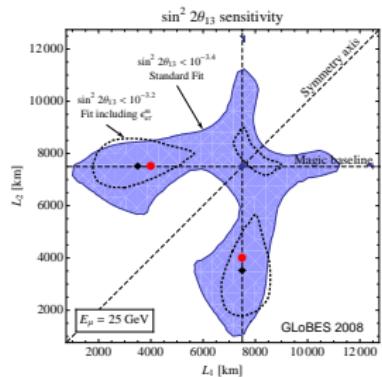
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# Optimization of baselines for $\theta_{13}$ , MH, CPV



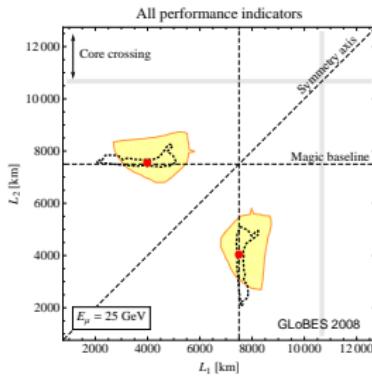
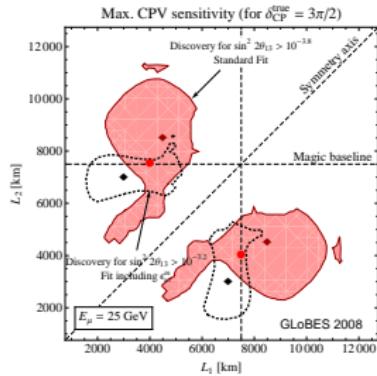
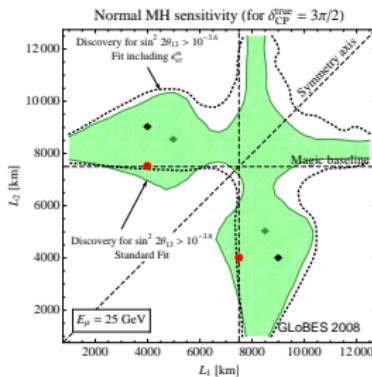
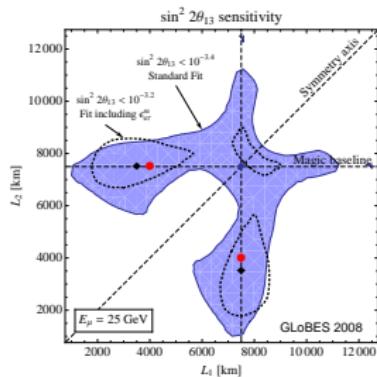
JK Ota Winter arXiv:0804.2261

# Optimization of baselines for $\theta_{13}$ , MH, CPV



Performance indicators:

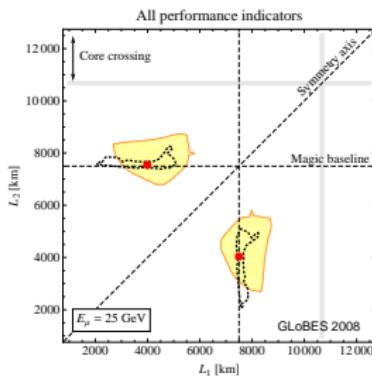
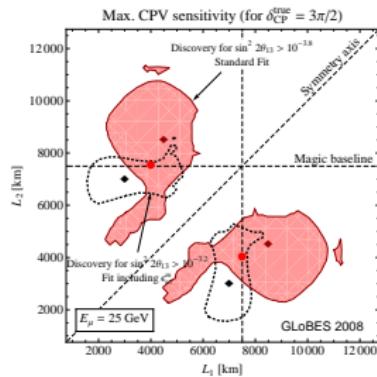
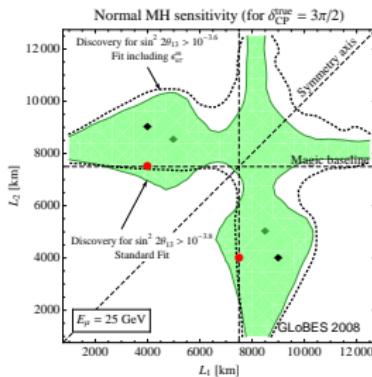
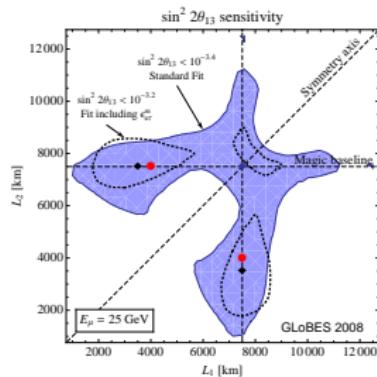
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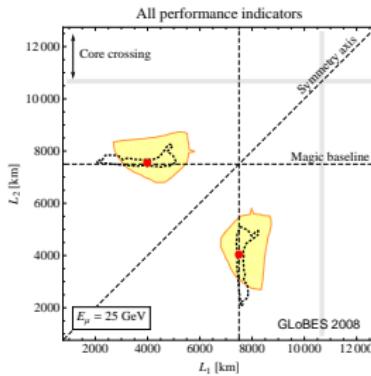
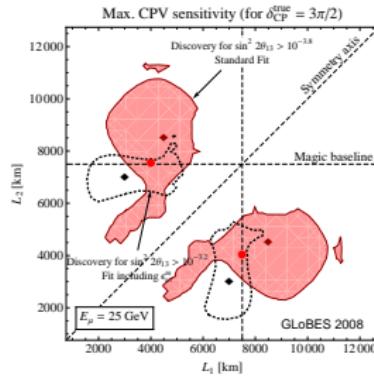
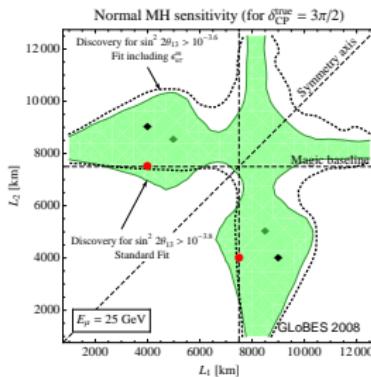
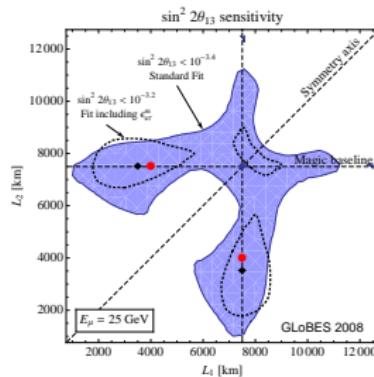
- $\sin^2 2\theta_{13}$  sensitivity:  
What is the new exclusion limit if  $\theta_{13}^{\text{true}} = 0$ ?

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# Optimization of baselines for $\theta_{13}$ , MH, CPV



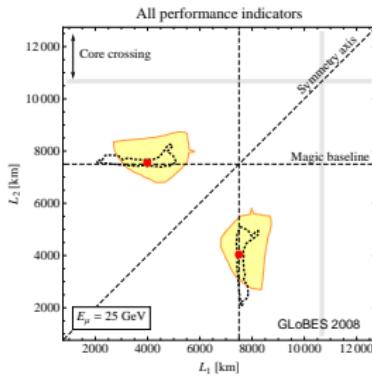
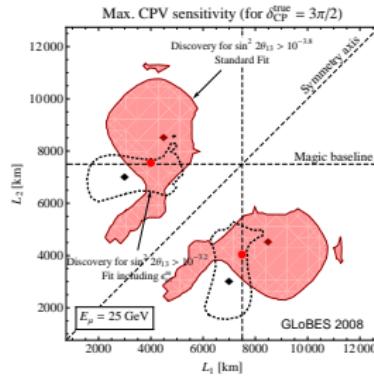
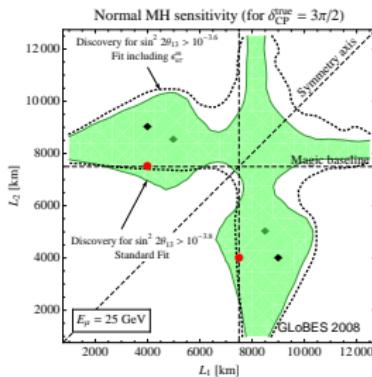
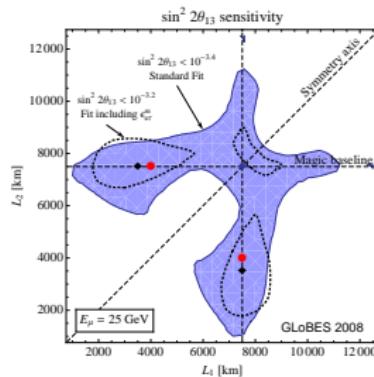
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**Conclusion:**

$L_1 = 4000$  km,  $L_2 = 7500$  km  
is close to optimal even if NSI are included in the fit.

# Optimization of baselines for $\theta_{13}$ , MH, CPV



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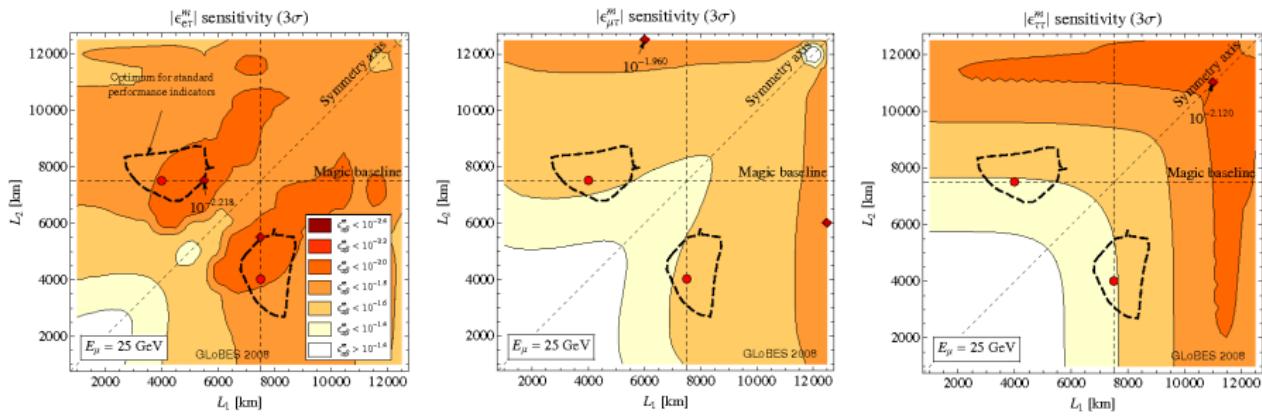
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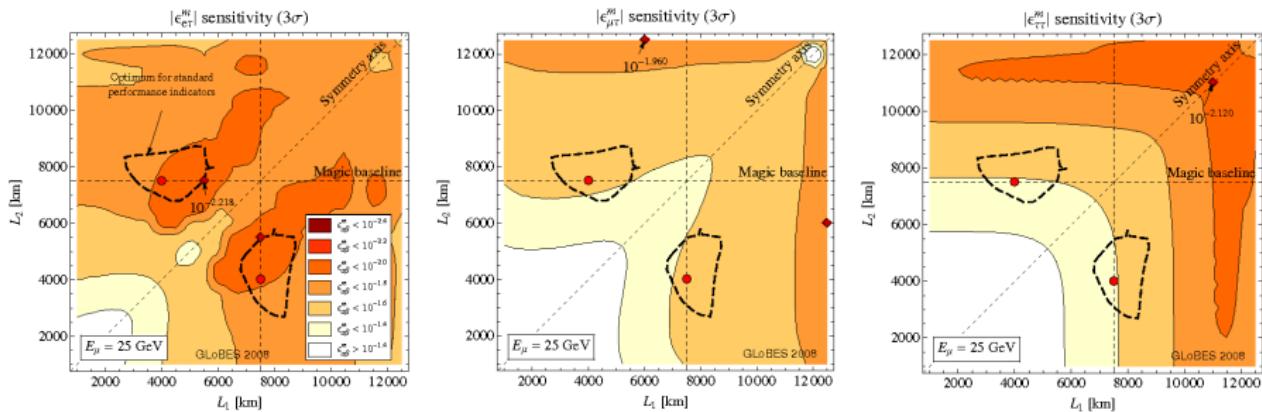
$L_1 = 4000$  km,  $L_2 = 7500$  km  
is close to optimal even if NSI are included in the fit.  
(We checked this also for the other  $\epsilon_{\alpha\beta}^m$ )

# Optimization of baselines for NSI



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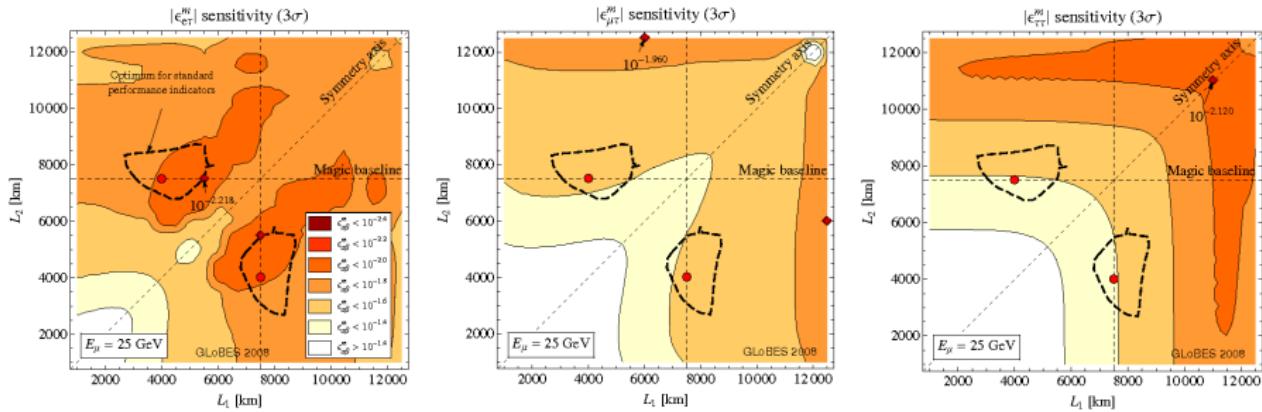
# Optimization of baselines for NSI



JK Ota Winter arXiv:0804.2261

- $L_1 = 4000$  km,  $L_2 = 7500$  km is OK for  $\epsilon_{e\tau}^m$

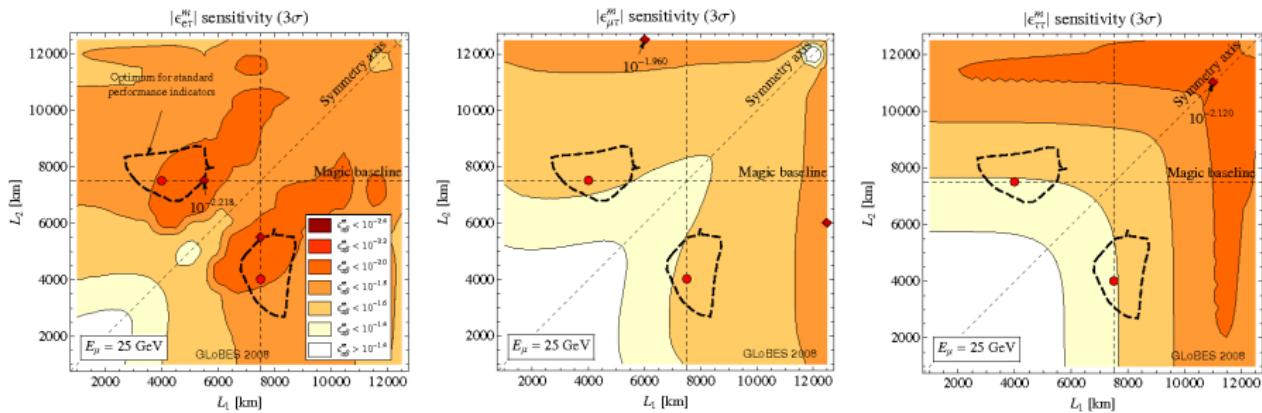
# Optimization of baselines for NSI



JK Ota Winter arXiv:0804.2261

- $L_1 = 4000$  km,  $L_2 = 7500$  km is OK for  $\epsilon_{e\tau}^m$
- For  $\epsilon_{\mu\tau}^m$  and  $\epsilon_{\tau\tau}^m$ , larger baselines are preferred.

# Optimization of baselines for NSI



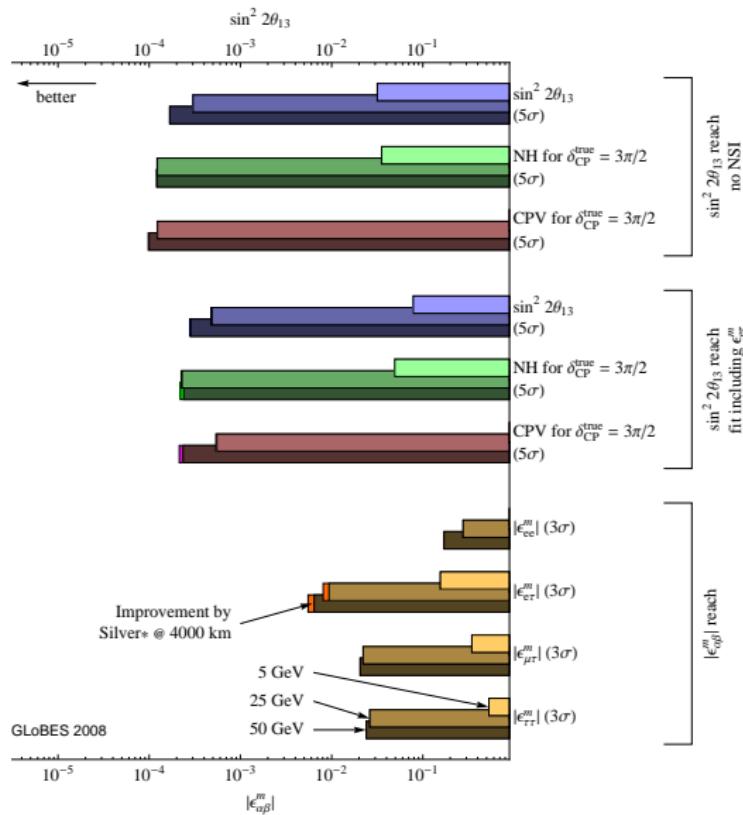
JK Ota Winter arXiv:0804.2261

- $L_1 = 4000 \text{ km}$ ,  $L_2 = 7500 \text{ km}$  is OK for  $\epsilon_{e\tau}^m$
- For  $\epsilon_{\mu\tau}^m$  and  $\epsilon_{\tau\tau}^m$ , larger baselines are preferred.
- Note: NSI sensitivity could be improved if longer baselines were combined with higher  $E_\mu$ .

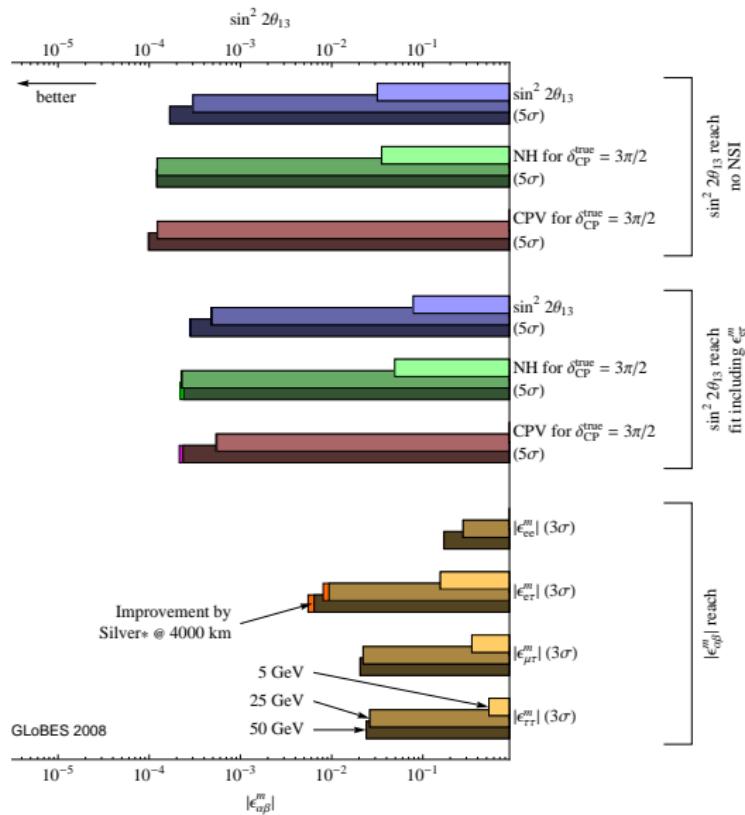
# Outline

- 1 Non-standard interactions in oscillation experiments
  - The general formalism
  - NSI in a neutrino factory
  - Analytical treatment of NSI in a neutrino factory
- 2 Optimization of a neutrino factory in the presence of NSI
  - Simulation details
  - Optimization of muon energy
  - Optimization of baselines
- 3 Summary and conclusions

# Summary and conclusions

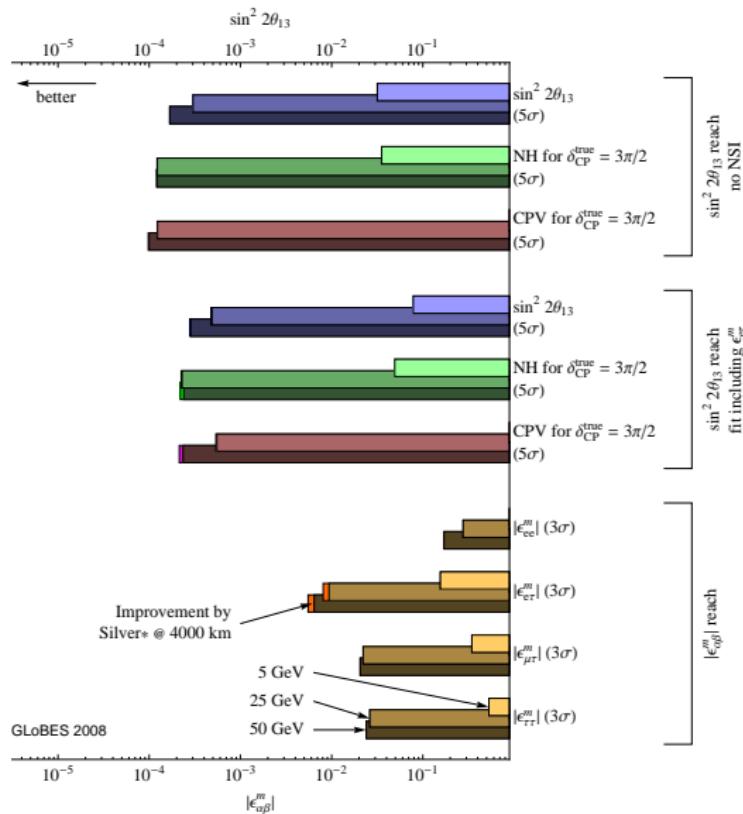


# Summary and conclusions



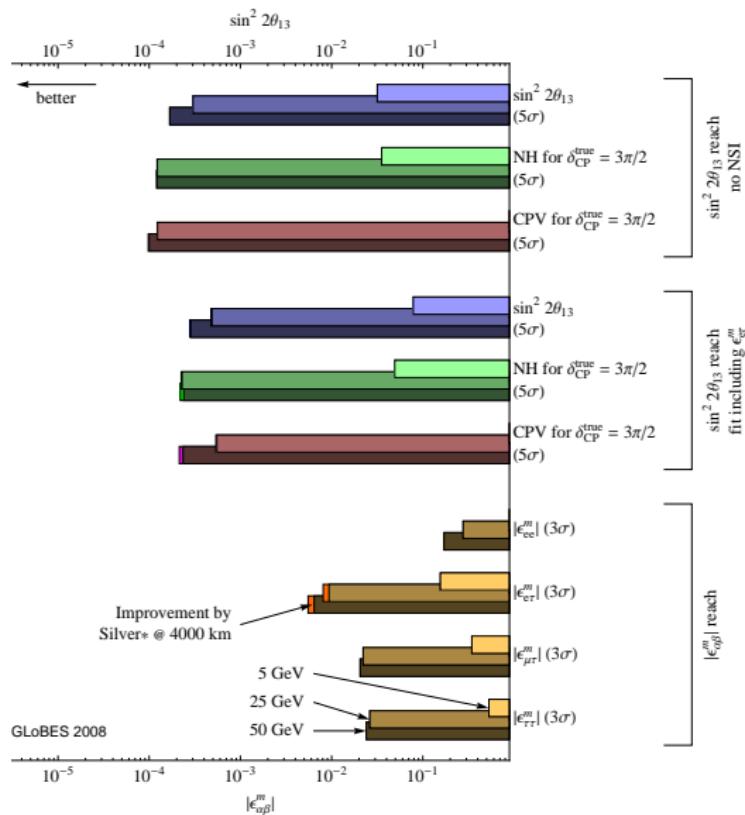
- $\nu$ -fact is a powerful tool to search for NSI, in particular  $\varepsilon_{e\tau}^m$ ,  $\varepsilon_{\mu\tau}^m$ , and  $\varepsilon_{\tau\tau}^m$ .

# Summary and conclusions



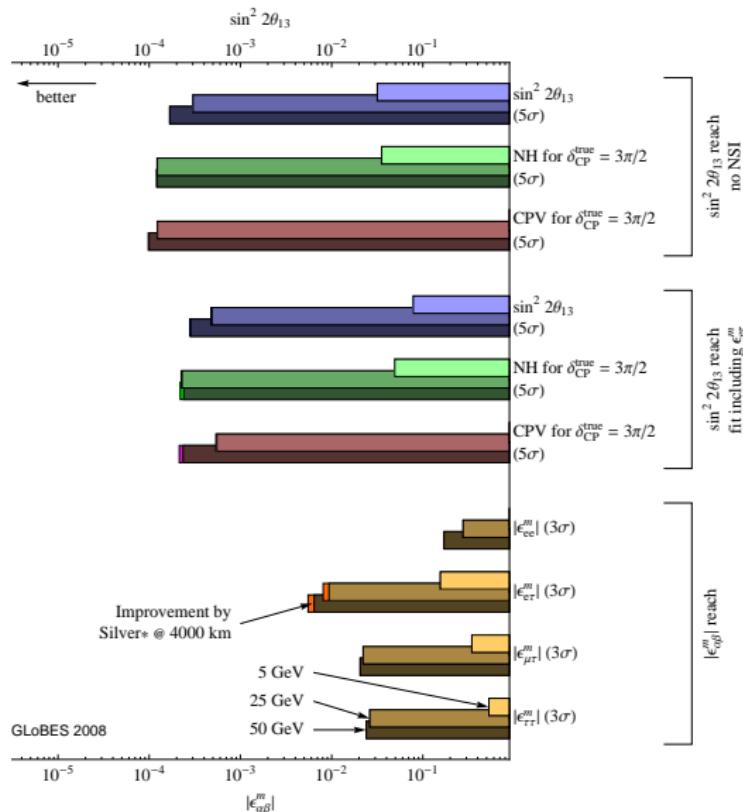
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- $E_\mu = 25 \text{ GeV}$  is OK.

# Summary and conclusions



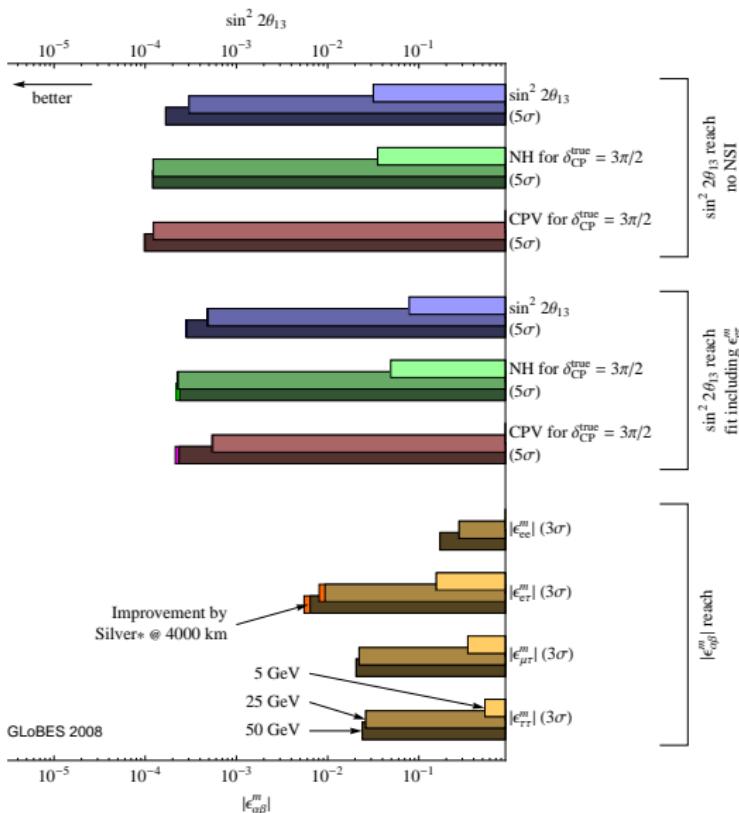
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# Summary and conclusions



- ν-fact is a powerful tool to search for NSI, in particular ε<sub>eτ</sub><sup>m</sup>, ε<sub>μτ</sub><sup>m</sup>, and ε<sub>ττ</sub><sup>m</sup>.
- E<sub>μ</sub> = 25 GeV is OK.
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- Some NSI slightly prefer longer baselines and higher energies.

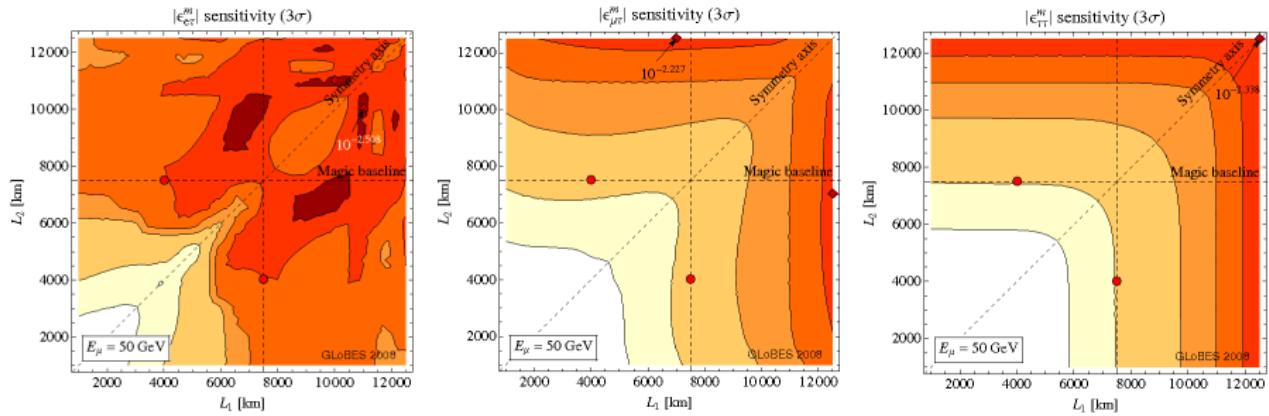
# Summary and conclusions



- $\nu$ -fact is a powerful tool to search for NSI, in particular  $\varepsilon_{e\tau}^m$ ,  $\varepsilon_{\mu\tau}^m$ , and  $\varepsilon_{\tau\tau}^m$ .
- $E_\mu = 25$  GeV is OK.
- $L_1 = 4000$  km,  $L_2 = 7500$  km is OK for  $\sin^2 2\theta_{13}$ , MH, and CPV, and NSI.
- Some NSI slightly prefer longer baselines and higher energies.
- **Silver channel can be omitted for standard physics and NSI, unless  $E_\mu$  is increased significantly.**

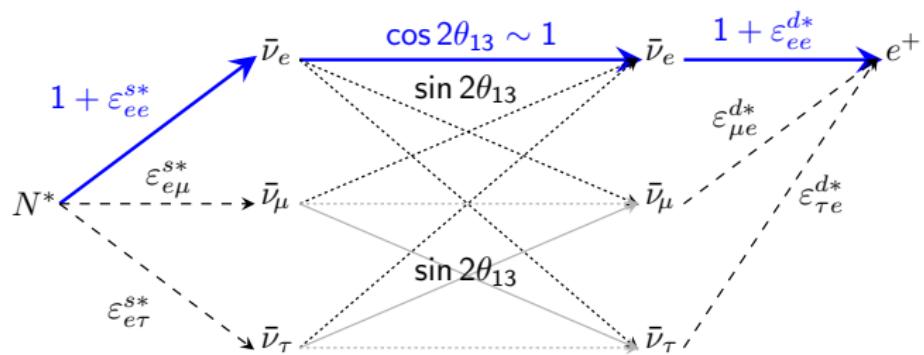
Thank you!

# Optimization of baselines for NSI ( $E_\mu = 50$ GeV)



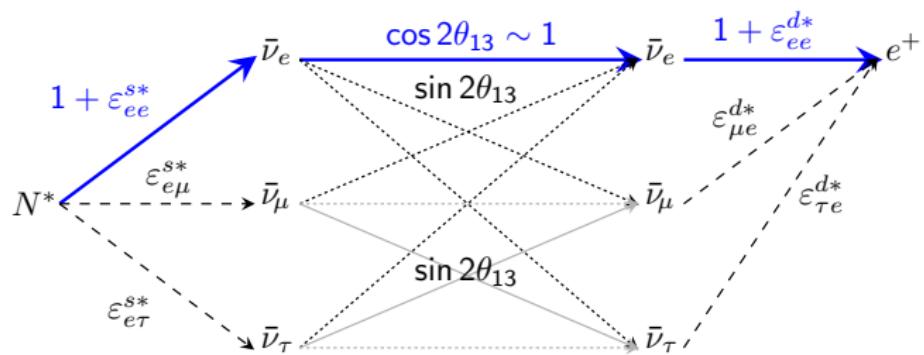
JK Ota Winter arXiv:0804.2261

# Qualitative arguments (NSI in source in detector)



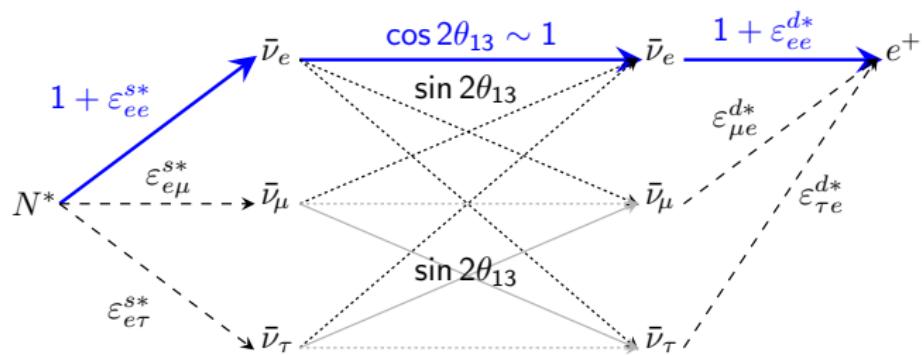
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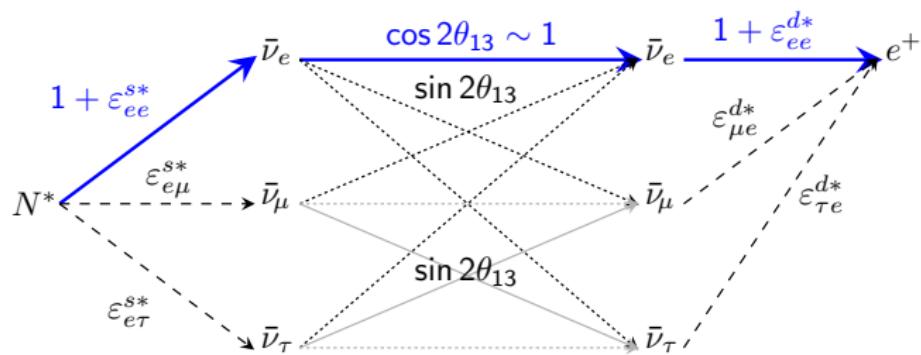
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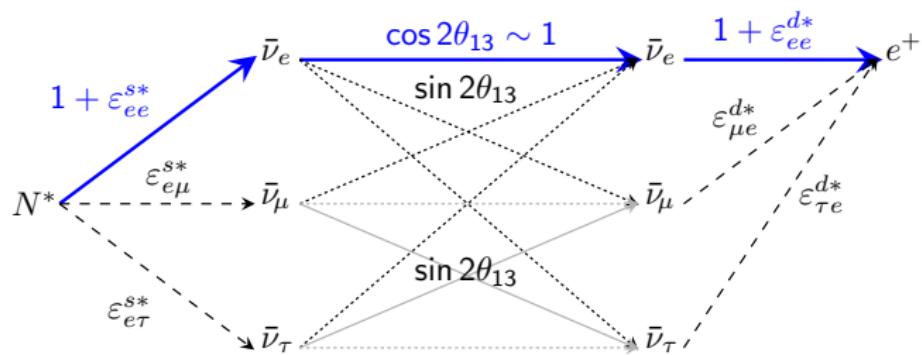
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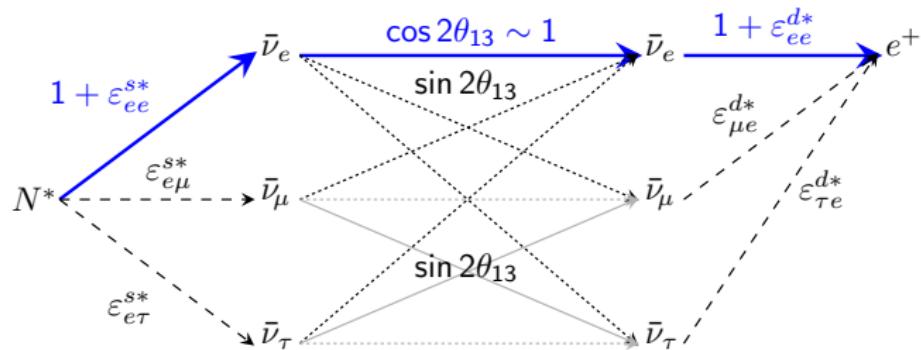
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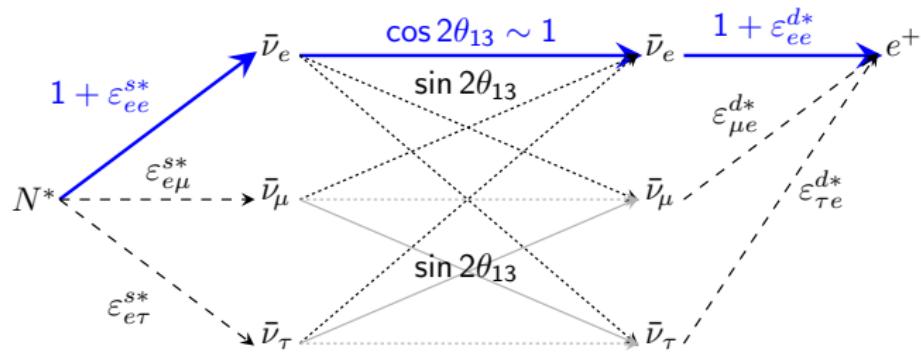
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- Assume only one  $\varepsilon$  parameter is sizeable

# Qualitative arguments (NSI in source in detector)



$N^* \xrightarrow{\epsilon_{ee}^{s*}} \bar{\nu}_e \rightarrow \bar{\nu}_e \rightarrow e^+$	$\mathcal{O}(\varepsilon)$	but: absorbed in flux uncertainty
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# Discovery reach for $\varepsilon_{e\mu}^m$ in a neutrino factory

- Discovery reach for  $\varepsilon_{e\mu}^m$ : Minimum value of  $|\varepsilon_{e\mu}^m|$  which can no longer be fitted with  $\varepsilon_{e\mu}^m = 0$  at a given C.L.

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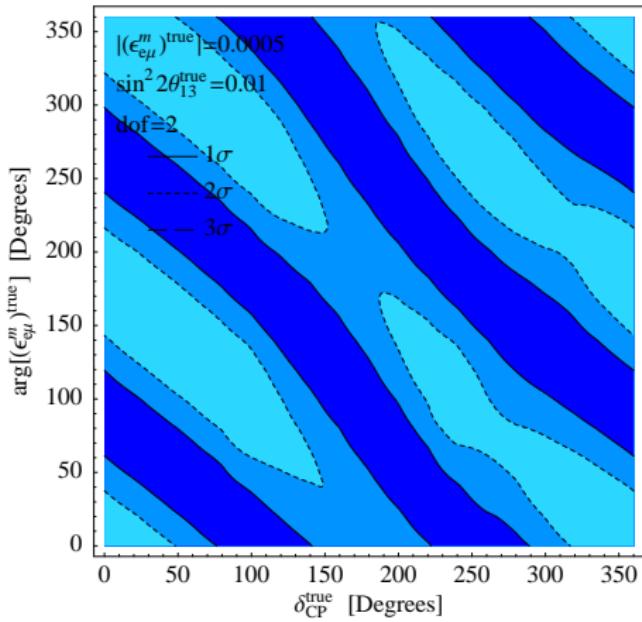
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# Discovery reach for $\varepsilon_{e\mu}^m$ in a neutrino factory

- $|\varepsilon_{e\mu}^m| = 0.5 \times 10^{-3}$
- $|\varepsilon_{e\mu}^m|$  too small



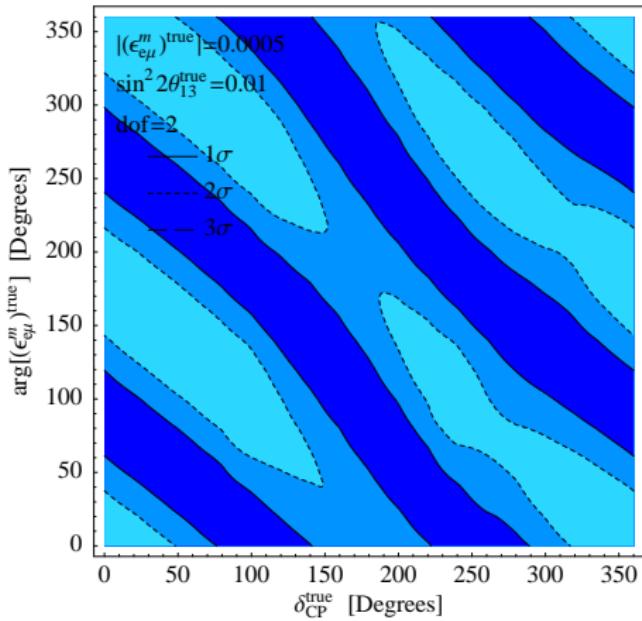
# Discovery reach for $\varepsilon_{e\mu}^m$ in a neutrino factory

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$\chi^2$  of standard oscillation fit is below  $3\sigma$  for all true values of  $\delta_{CP}$  and  $\arg \varepsilon_{e\mu}^m$ .



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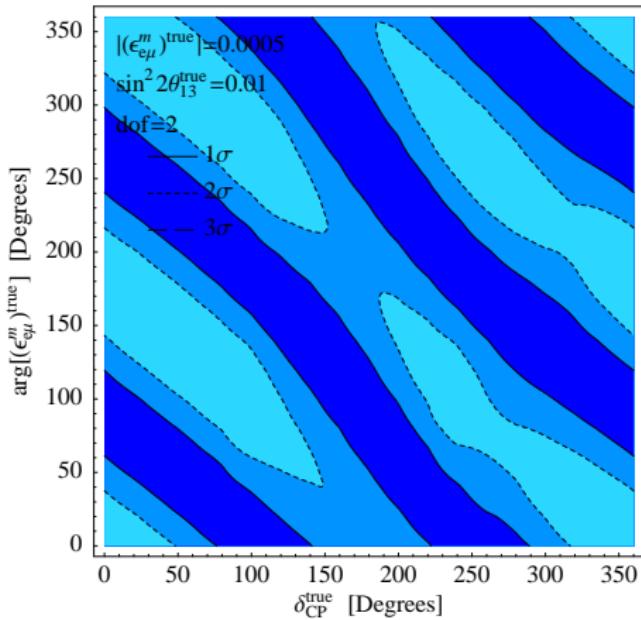
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No chance for discovery



# Discovery reach for $\varepsilon_{e\mu}^m$ in a neutrino factory

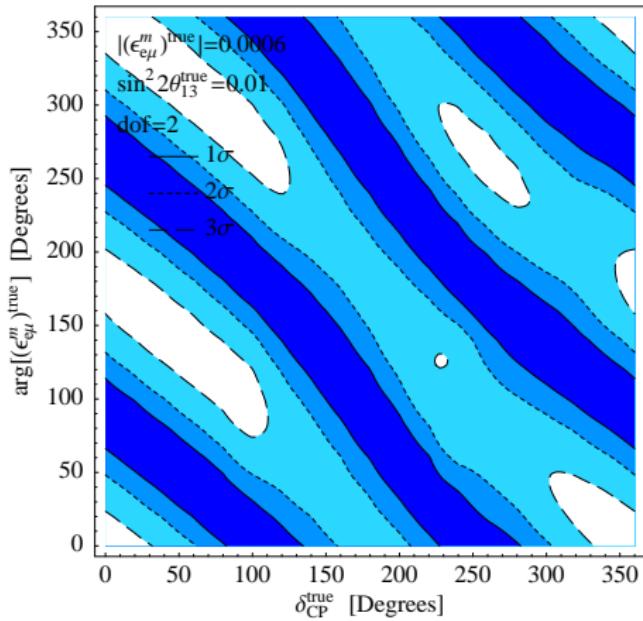
- $|\varepsilon_{e\mu}^m| = 0.6 \times 10^{-3}$
- $|\varepsilon_{e\mu}^m|$  becomes larger



For some combinations of  $\delta_{CP}$  and  $\arg \varepsilon_{e\mu}^m$ , the standard oscillation fit becomes worse than  $3\sigma$  (white islands appear).



Discovery possible for favorable phase combinations



# Discovery reach for $\varepsilon_{e\mu}^m$ in a neutrino factory

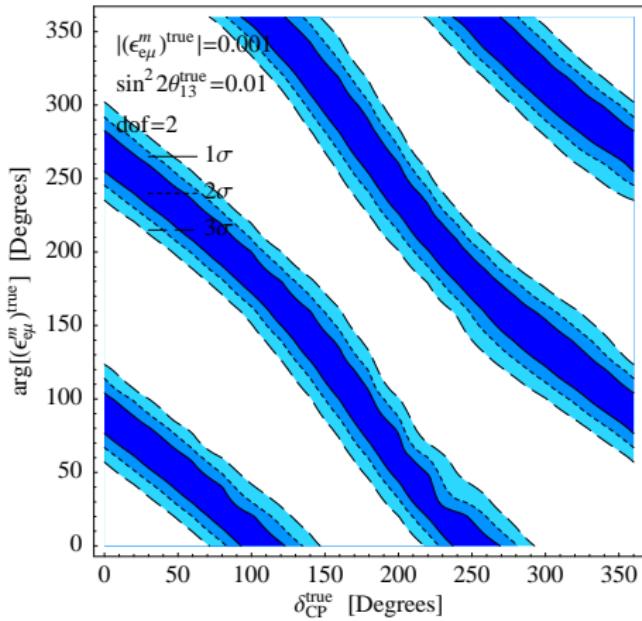
- $|\varepsilon_{e\mu}^m| = 1 \times 10^{-3}$
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Discovery possible for favorable phase combinations



# Discovery reach for $\varepsilon_{e\mu}^m$ in a neutrino factory

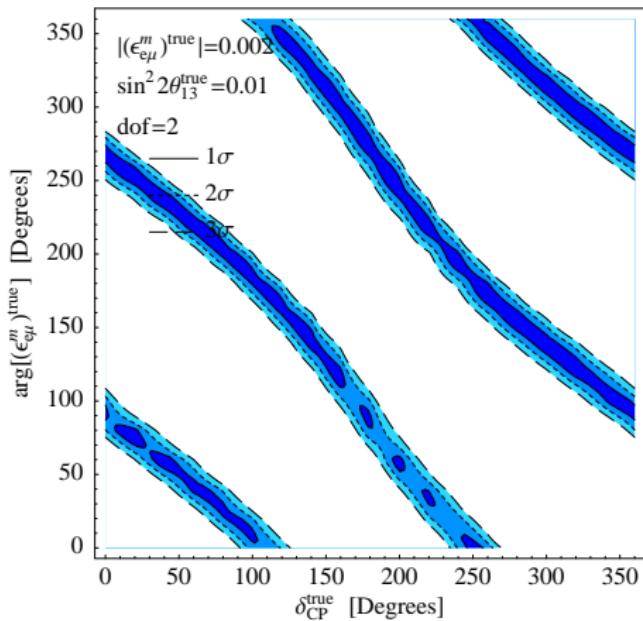
- $|\varepsilon_{e\mu}^m| = 2 \times 10^{-3}$
- $|\varepsilon_{e\mu}^m|$  becomes larger



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Discovery possible for favorable phase combinations



# Discovery reach for $\varepsilon_{e\mu}^m$ in a neutrino factory

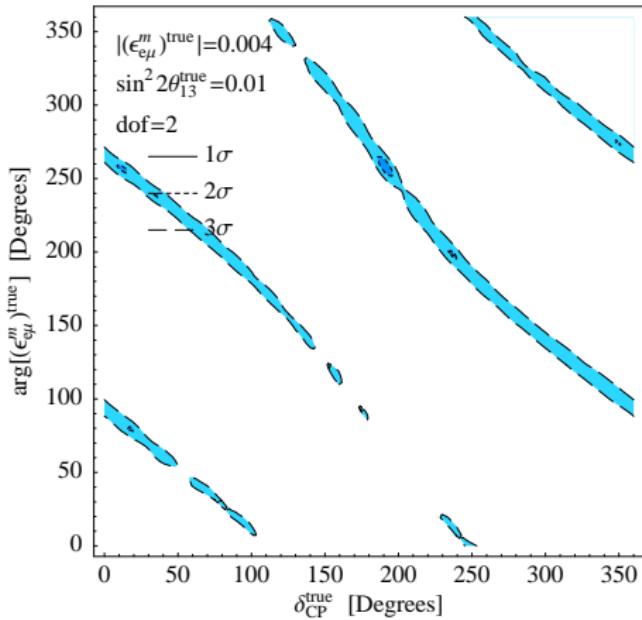
- $|\varepsilon_{e\mu}^m| = 4 \times 10^{-3}$
- $|\varepsilon_{e\mu}^m|$  becomes larger



For some combinations of  $\delta_{CP}$  and  $\arg \varepsilon_{e\mu}^m$ , the standard oscillation fit becomes worse than  $3\sigma$  (white islands appear).

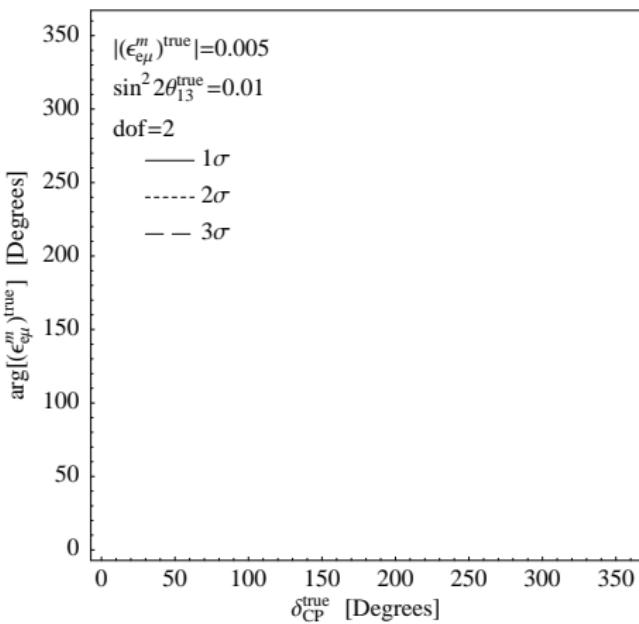


Discovery possible for favorable phase combinations

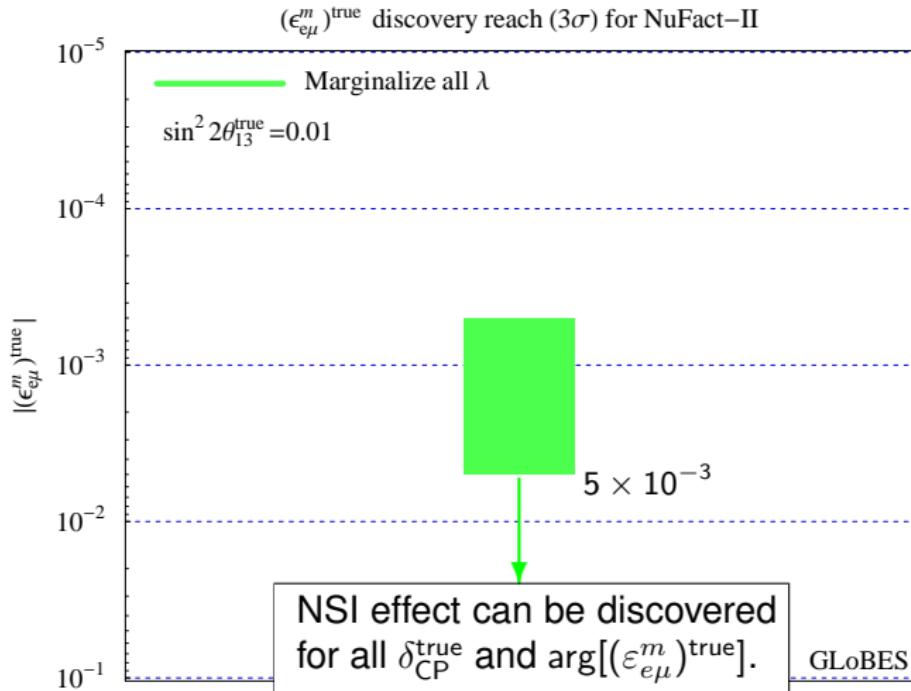


# Discovery reach for $\varepsilon_{e\mu}^m$ in a neutrino factory

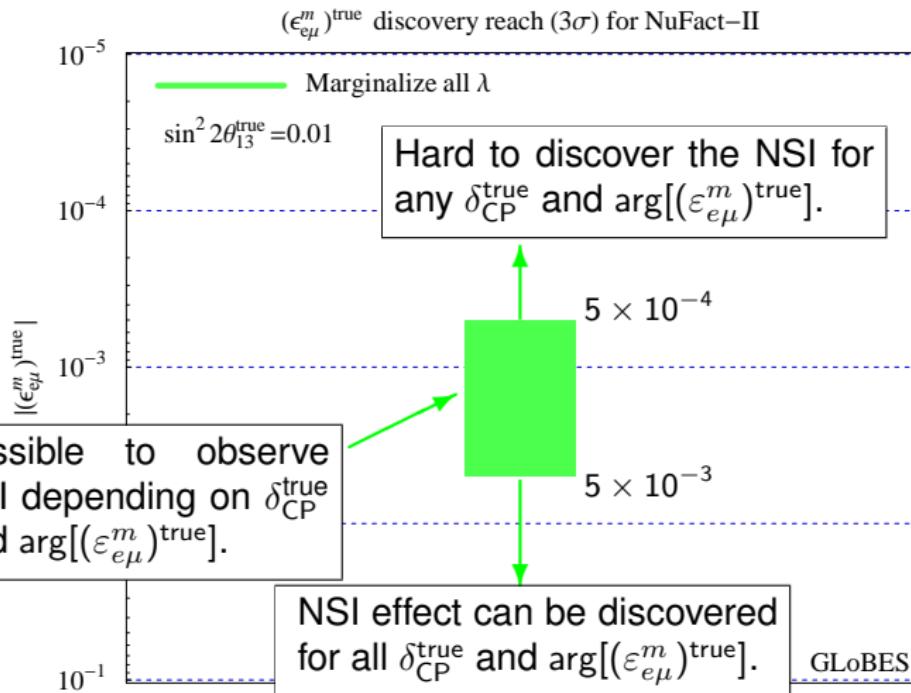
- $|\varepsilon_{e\mu}^m| = 5 \times 10^{-3}$
- $|\varepsilon_{e\mu}^m|$  is large enough
  - $\downarrow$
  - $\chi^2$  of standard oscillation fit exceeds  $3\sigma$  in the whole parameter plane.
  - $\downarrow$
  - Discovery is possible for any phase combination



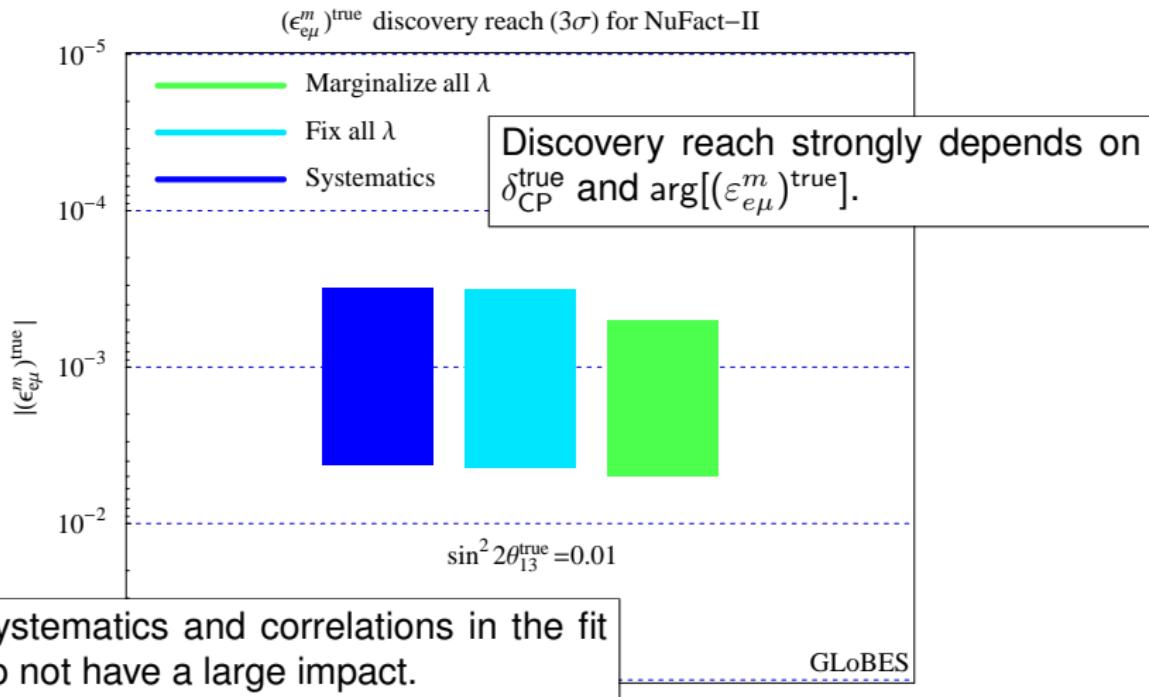
# Summary of the discovery reach for $\varepsilon_{e\mu}^m$



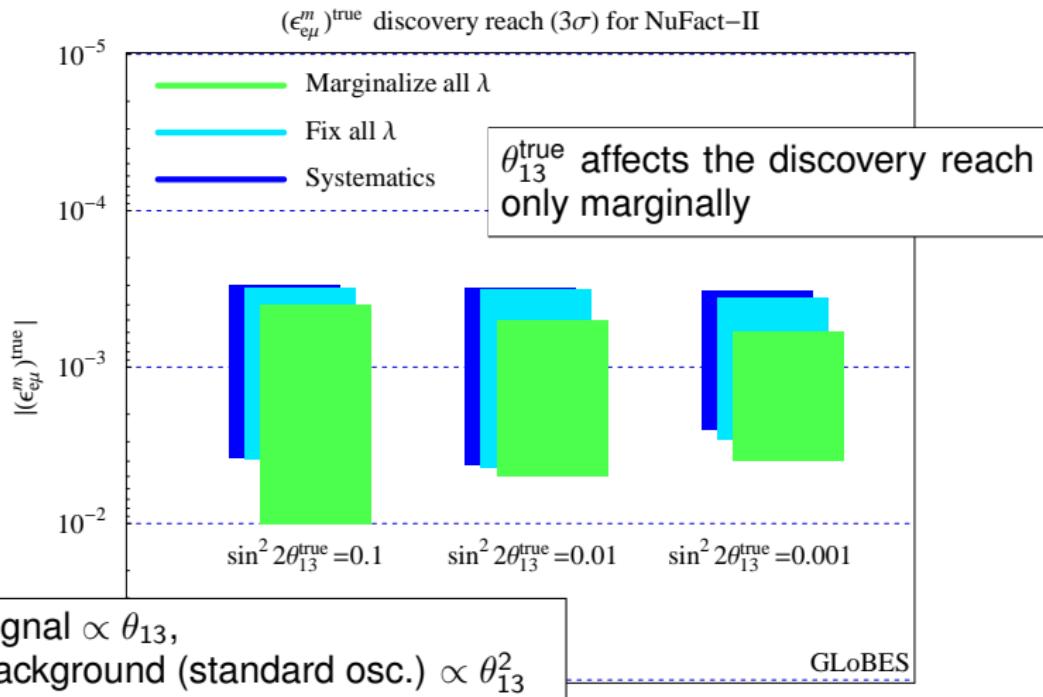
# Summary of the discovery reach for $\varepsilon_{e\mu}^m$



# Summary of the discovery reach for $\varepsilon_{e\mu}^m$



# Summary of the discovery reach for $\varepsilon_{e\mu}^m$



# Discovery reach for $\varepsilon_{e\tau}^m$ and $\varepsilon_{e\mu}^s$ in a neutrino factory

